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Luminescence of quasi-2DEG in heterostructures based on PbS films

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ABSTRACT

The paper deals with the problem of luminescence due to non-equilibrium charge carriers transfer between the quasi-2D electron system localized in the space-charge region of the heterostructures based on lead sulfide films (up to 3 μm thickness) and zinc selenide substrates surrounded by the wide gap semiconductor region. The processes of electro- and photoluminescence are studied, the band diagram is proposed and the main parameters of the structure PbS/quasi-2DEG/ZnSe are calculated.

INTRODUCTION

Highest performance of modern often requires more sophisticated structures and non-destructive methods of their properties analysis. Epitaxial techniques offer important advantages in comparison with the bulk grown ones: lower temperature, shorter growth time and reduced precipitation problems enable the growth of large-area samples with good parameters. At present, MBE (molecular-beam technology) is the most mature method of device-quality layer fabrication. In particular, semiconductor devices based on A^2B^6-A^4B^6 heterostructures are of special importance due to the well-known "window-effect" as well as a possibility to act as a system of quasi-2D or quasi-3D charge carriers, as it was shown earlier [1]. The paper presents results of photoluminescence studies performed at 77 K on the isotype n-n-heterojunctions PbS/ZnSe obtained by the MBE technology.

EXPERIMENTAL DETAILS

Preparation of the samples.

The investigated isotype n-n-heterostructures ZnSe/PbS were grown by the MBE technology of lead sulfide ($E_g = 0.41$ eV) films with thickness up to 3 μm on the (110)-oriented ZnSe ($E_g = 2.72$ eV) wafers under the substrate temperature $T_s = 540$ K (the vacuum level in the effusion cell was estimated to be about 10^{-9} Tor). The samples of 1.5x3.5 mm^2 size characterized by the film surface homogeneity were selected for the examinations. Parameters of the contacting materials are listed in Table 1.

Table 1.
Parameters of the components of the investigated heterostructures

Material	Parameter
ZnSe	$E_g = 2.72$ eV
	a = 5.668 Å
	$\varepsilon = 9.1\varepsilon_0$
	$n_e = (7.8 \cdot 10^{16} - 2.6 \cdot 10^{17})$ cm^{-3}
PbS:Na	$E_g = 0.41$ eV
	a = 5.940 Å
	$\varepsilon = 175\varepsilon_0$
	$n_e = (2 - 8) \cdot 10^{15}$ cm^{-3}

Results of electric-field measurements.

The electrophysical studies described for the first time in [2].were shown that the heterostructures based on the materials mentioned in the present article are abrupt heterojunctions.

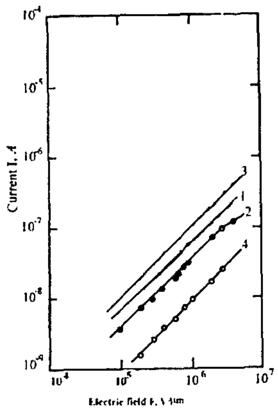

Fig. 1. Field dependencies of the examined heterostructure n-PbS/n-ZnSe. Functions 1, 3 are forward sections and functions 2, 4 are reverse ones at 300 and 77 K, respectively.

The further electric-field measurements (Fig. 1) carried out on the as-grown specimens demonstrated that the processes of the charge carriers transfer are strongly effected by the space-charge region of the heterojunction formed by the surface electron states at the interface. The numerical analysis of the experimental I-F-measurements (where I stands for the current flowing through the heterojunction and F denotes the external electric field) showed that the I-F-function can be expressed according to the model developed in [3]:

$$I = K_{tun} \frac{2\varepsilon_0 \varepsilon A_{el} v_{sat}}{LW} F , \qquad (1)$$

where K_{tun} is the transparency coefficient of the potential barrier formed at the interface of the heterostructure depending on the energy spectrum of the surface electron states [2], ε is the dielectric constant], A_{el} is an electrical area of the investigated sample, L takes care of the sample thickness, W stands for the width of the space-charge region determining from the capacitance-voltage measurements [2] and v_{sat} is a complex function strongly influenced by the parameters of the contacting materials. Such a field dependence indicates on the inhomogeneous (quantum wells continuum, QW-continuum) structure of the potential barrier which determines not only the electric characteristics of the heterostructure but also the emission properties of the grown samples.

Electro- and photoluminescent studies.

Photoluminescence (PL) of the investigated structures was excited by the light source of the wavelength λ centered around 290 nm. Electroluminescence (EL) was excited by the electrostatic field, $F = (0.9 - 1.8) \cdot 10^6$ V/m. Both PL and EL spectra were registered at T = 77 K in the wavelength range from 0.48 up to 0.8 μm. As it is shown, both PL and EL spectra are appeared as the wide Gaussian-like bands in the wavelength range 0.53-0.80 μm describing by the expression [5]

$$I(\hbar\omega) \sim \omega^2 (\hbar\omega - \Delta)^{1/2} \exp[-(\hbar\omega - \Delta)/k_B T], \qquad (2)$$

where Δ stands for the value of the integrated potential barrier consisting of the QW-continuum, ω is frequency of the excited light source.

The energy positions of the emitted radiation maximums are estimated to be about 1.97-2.00 eV; These results show that the emission processes are take place in the subsurface region of the wide-gap material. such a value corresponds neither lead sulfide nor zinc selenide energy parameters as well as the energy levels of the known and uncontrolled impurities. The previous studies [1] were shown the formation of the quasi-2D electron system at the interface of the examined heterostructures. The experimental results obtained under the electro- and photoluminescent measurements had allowed to conclude that the investigated structure presents a multi-QW continuum localized at the interface.

The experimental results are plotted in Fig. 2.

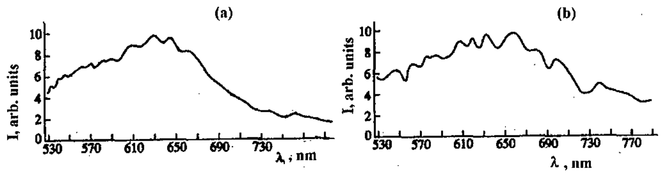

Fig. 2. Photoluminescence (a) and electroluminescence spectra of the investigated n-PbS/n-ZnSe heterostructure. T = 77 K.

DISCUSSION

As it was mentioned above, the investigated isotype n-n-heterostructure PbS/ZnSe is appeared as a heterojunction with QW-continuum at the interface. The experimental data obtained from the luminescent studies showed that the non-equilibrium charge carriers were excited in the subsurface region of the wide-gap substrate adjacent to the space-charge region of the structure, then the carriers were confined in the QW-continuum and have relaxed energetically with radiative recombination. In the other words, this so-called "graded barrier" [6] acted as a suppressor of the carrier trapping at low temperatures, leading to an improved excitation transfer from the barriers to quantum wells (Fig. 3).

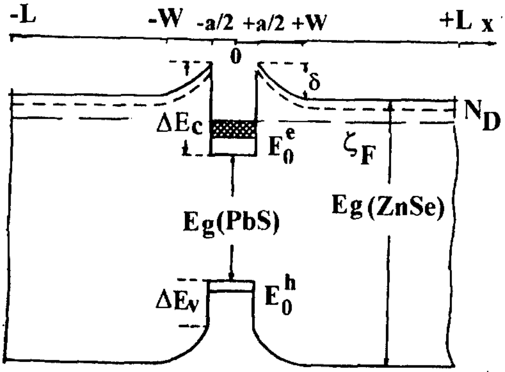

Fig. 3.Energy band diagram of the examined heterostructure constructed according to [4](non-scaled, the main parameters are listed in Table 1)
ΔE_c and ΔE_v are the conduction band and valence band discontinuities (the method of calculation is reported in [2]), E_0^e, E_0^h are energy positions of the electron and hole levels in quantum well, respectively, a is the quantum well width ($a = (\varepsilon_0 \varepsilon k_B T / e^2 N_D)^{1.2}$), other notes are explained in the text.

The barrier value δ was calculated according to the measurements performed previously [1] and using the Schottky approximation for the depletion layers surrounding the quantum well, we have [4]

$$(8\varepsilon_0 \varepsilon N_D \delta)^{1/2} = n_s^0 + \Delta n_s - \Delta p_s, \qquad (3)$$

where N_D is donor concentration in the wide-gap material, δ is the potential barrier, n_s^0 is the surface concentration of the equilibrium electrons, Δn_S stands for the concentration of the non-equilibrium electrons and Δp_S takes care for the concentration of the non-equilibrium holes.

Under equilibrium conditions $\Delta n_S = \Delta p_S = 0$ and

$$n_s^0 = \frac{m_e k_B T}{\pi \hbar^2} \ln\left[1 + \exp\left(\frac{\xi + \Delta E_c - E_0^e - \delta_0}{k_B T}\right)\right]. \qquad (4)$$

Here ξ is the Fermi level position in the wide-gap substrate, ΔE_c is conduction band discontinuity (calculated according to the Harrison model in [2]), m_e is the electron effective mass in ZnSe, E_0^e is energy of electron level in the quantum well. The solution of the equations (3) and (4) makes it possible to calculate the equilibrium values of n_s^0 and δ. Results of the calculation are plotted in Figs. 3, 4.

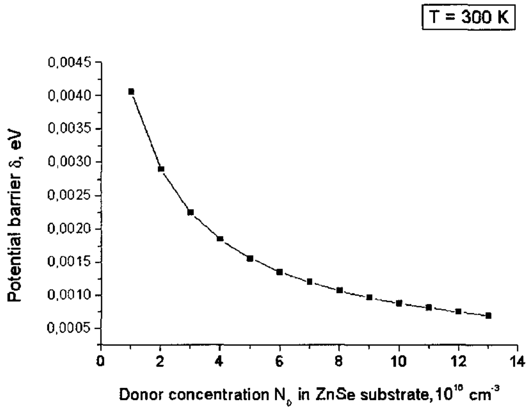

Fig. 4. Potential barrier formed by the QW-continuum localized at the interface of the heterostructure vs. donors concentration in ZnSe substrate..

As it is shown in Fig.4, the value of the barrier δ decreases as the donor concentration in the substrate increases, and the life-time of the non-equilibrium carriers has to become greater [4]. At the same time, the intensity of the luminescence spectra in long-wave interval is comparable with the same characteristic in the short-wave region. Thus, the presence of the potential barrier δ increases the effective width of the quantum well for the non-equilibrium carriers under the low level of excitation.

CONCLUSIONS

Isotype n-n-heterostructures based on thin lead sulfide films and zinc selenide demonstrated good emission characteristics under 77 K strongly depending on the properties of the space charge region. The results of luminescent (PL and EL) experiments have been shown the formation of quantum-inhomogeneous barrier at the interface of the examined n-PbS/n-ZnSe heterostructure and the technological possibility of monitoring the carriers confinement and ejection in the region of QW-continuum by means of proper doping of the substrate material.

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